The analysis showed the same time delays of onset of bursts at different frequencies as had earlier been observed (e.g. Payne-Scott et al., 1947), as well as supporting the observation of both outward and inward movement of sources through successive plasma levels in the solar atmosphere, as had been observed by Payne-Scott and Little (1952). All frequencies showed a tendency to lag 3,000 MHz, suggesting a simultaneous movement up and down from the level of zero refractive index at the frequency which occurred first.

In terms of correlations with other phenomena, the analysis showed that nearly all flares and their terrestrial effects (i.e. magnetic crochets and radio fadeouts) were associated with radio bursts. Only 1% of flares and fadeouts and 2% of crochets were not associated with bursts. There was also a rough correlation between the intensity of bursts, flares, fadeouts and crochets. The onset of the bursts appeared to coincide with the onset of flares and crochets, but preceded fadeouts by about two minutes. As all types of bursts were included in the analysis there were many more bursts observed than flare, fadeouts and crochets.

This was effectively the end of the solar burst research at Potts Hill. Much progress had been made in a relatively short period of time, providing a solid foundation of observational results, through accurate position measurements, polarisation studies and long-term statistical analyse.

10.5.2. Cosmic Research

The original reason for establishing the Potts Hill field station was to consolidate the solar observations leading up to the 1 November 1948 solar eclipse. Solar research was therefore the major focus of the field station in its initial years. This focus began to change during 1949 as interest in discrete cosmic sources
grew. Initially these investigations were made by using the solar instruments when solar observation was not possible, such as between sunset and sunrise (e.g. Mills and Thomas, 1951; Piddington and Minnett, 1951a). In 1951 Ewen and Purcell (1951) working at Harvard detected the 1,420 MHz ($\lambda = 21$cm) Hydrogen emission-line that had been predicted many years earlier by van de Hulst (1945). This discovery was quickly confirmed in Australia (Pawsey, 1951b) and lead to a new branch of investigations at Potts Hill and to the construction of the first instrument there dedicated to cosmic research.

In the second half of the life of the Potts Hill field station cosmic source investigations dominated the research program. Figure 137 illustrates the rise of cosmic investigations and hence publications produced as a result of research at Potts Hill.

This section describes these cosmic investigations in three main parts. The first examines the discrete source investigations and survey work, and is then is followed by a review of the H-line programs. Finally a brief discussion of the contribution made to Jupiter burst observations is provided.

10.5.2.1. Discrete Sources and Surveys

After a very short foray into solar research with Christiansen and Yabsley (1949b), Mills turned his attention to the investigation of discrete cosmic sources. Together with Thomas, he used the swept-lobe interferometer in its conventional interferometer configuration to investigate the discrete radio source in Cygnus that had been discovered by Hey, Parsons and Phillips (1946). At Dover Heights significant progress had been made in identifying optical counterparts to three of eight discrete sources (Bolton et al.,...
1949). However, identification of Cygnus A remained problematic (Bolton and Stanley, 1948a,b; Ryle and Smith, 1948). After a number of further investigations (Little and Lovell, 1950; Smith, 1950; Stanley and Slee, 1950) the fluctuations that had been observed from the source were determined to originate in the ionosphere and although accuracy of the positional estimates was improved, no optical identification of the source was made. In another example of an event that contributed to an increasing antagonistic relationship between the Australian group and their Cambridge counterparts, Stanley and Slee examined their 1948 measurements of source fluctuations and were confident that they were caused by diffraction in the intervening medium and were not intrinsic to the source itself. They sought the help of their Cambridge colleagues to confirm this result. Subsequently the Cambridge Radio Astronomy group collaborated with radio astronomers at Jodrell Bank to confirm this, but no acknowledgement was made of the contribution of Stanley or Slee and they were left to belatedly publish their result after the Cambridge and Jodrell Bank papers appeared in *Nature* (Slee, 1994: 523).

It was with this background that Mills and Thomas undertook investigations of Cygnus A from May to December 1949. From Potts Hill, the source was relatively low in the northern sky rising to a maximum of only 16° above the horizon. This made position measurement at the relatively low frequency of 97 MHz difficult and also subject to significant refraction and ground reflection errors. As such, these factors needed to be included in the interferometry declination formula.

\[
\cos \delta = \frac{n \lambda}{d \sin H} (1 + R \tan E) \tag{8}
\]

where

- \( \lambda \) is the wavelength;
- \( d \) is the distance between aerials;
- \( n \) is the number of a minimum in the interference pattern counting from an assumed central minimum;
- \( H_n \) is the corrected hour angle at which the \( n \)th minimum occurs;
- \( R_n \) is the vertical refraction; and
- \( E_n \) is the angular elevation of the source above the horizon.

The right ascension of the source was determined from the time of transit. In practise it was necessary to conduct the measurements with two different aerial spacings to remove the ambiguity between which minimum of the interference pattern was related to the transit of the source. The averages of twelve minima either side of the central minimum were used to calculate the declination from a single observing run. The minima were used because the positions of the maxima are difficult to define because of
atmospheric scintillations. This is clearly illustrated in Figure 138 where the second and third maxima from the left show scintillations. Mills and Thomas paid careful attention to correcting and documenting all of the different types of errors that would impact the position estimate. For example they allowed for a more accurate estimate of the speed of light in the atmosphere for the given conditions (2.9969 × 10^{10} cm/second), as using the standard value of 3.00 × 10^{10} cm/second would yield a 3 arc minute error in the declination. Figure 138 shows a typical record of the source transiting the interferometer beams and producing the interference pattern.

![Figure 138: A typical record of Cygnus A source transiting the interferometer beams (after Mills and Thomas, 1951: 160).](image)

After some months of observations the following position estimate was given:

R.A. 19 hr. 57 min. 37 sec.

Dec. 40° 34'

with a probable error of 6 seconds in Right Ascension and 3 minutes in Declination. In private communication with Rudolf Minkowski of Mount Wilson Observatory, Mills identified a 15^{th} magnitude nebula at a distance of 10^7 parsec as being within the positional error box, although its position quoted in the paper was slightly inaccurate and was later corrected by Baade in a personal communication (see Mills and Thomas, 1951: 461n). It was one of the brightest galaxies in a cluster of galaxies, however nothing else appeared to distinguish this particular galaxy as the source of such strong radio emission. Minkowski wrote to Mills advising that he did not think it was permissible to identify the source with one of the faint extragalactic nebulae and therefore a more accurate position estimate was needed to unambiguously distinguish between the other faint nebulae (see Baade and Minkowski, 1954). As it transpired the faint galaxy that was the subject of the discussion turned out to be the source of the extraordinary strong radio emission when a more accurate position was ultimately determined by the Cambridge group (Smith, 1951).
This position was used by Baade and Minkowski (1954) to unambiguously identify the source galaxy. The final photographically-determined position was:

- R.A. 19 hr. 57 min. 44.49 sec.
- Dec. 40° 35' 46.3”

Figure 139 shows a modern optical image of Cygnus A with a 0.05 degree field of view.

For comparison, Figure 140 shows the image plate used by Mills and Thomas in the original attempted identification. The actual position of Cygnus A has been added to the image, marked by the cross-hair, and is 7.49 arc seconds in right ascension and 1’ 46.3” in declination from the position estimated by Mills and Thomas.
In their published paper Mills and Thomas (1951) concluded that it was unlikely that the source of the emission was the suspect galaxy; instead they concluded that the source was most likely located in some nearby faint star of abnormal properties. As no proper motion of the source was detected, they concluded that the source must be at a distance at least forty times the radius of Pluto’s orbit, and they therefore also ruled out suggestions that the discrete sources of radio emission were associated with nearby comets (Menzel, 1950).

Polarisation measurement of Cygnus A was also attempted, but no change in the interference pattern could be detected while switching between the horizontal and vertical elements of the Yagi antennas. This indicated that if there was any polarisation of the source radiation it was less than 3%.

Mills and Thomas also undertook a detailed analysis of the source fluctuations observed. Figure 141 shows examples of the ‘fast’ and ‘slow’ fluctuations as well as an example of the correlation between signals received on aerials spaced 300 metres apart.

Figure 140: The original image plate (colour inverted) with the position estimate rectangle shown together with the actual position of Cygnus A marked by the cross hair (after Mills and Thomas, 1951: Plate 1A).
Figure 141: Examples of fluctuations observed in the emissions from Cygnus A. The top chart shows an example of the 'fast' fluctuations. The middle chart shows an example of the 'slow' fluctuations, and the bottom two charts show the correlation of signals between two aerials spaced 300 metres apart (after Mills and Thomas, 1951: 166).

Indices were calculated for the different fluctuation types and compared with the available geophysical data to look for possible correlations. The 'fast' fluctuation index was calculated by measuring the maximum and minimum intensities within each aerial lobe and hence calculating the ratio of the difference to their mean value. This was similar to the method used by Stanley and Slee in their investigations of the
fluctuations (Stanley and Slee, 1950: 245). The ‘slow’ fluctuation index was a measure of the scatter of the average intensity of individual lobes from the mean level of all lobes in an observing period. A further ‘deviation’ index was calculated as the scatter of the lobe-minima transit times over a period of one hour. Using these indices a direct correlation was found between the fast fluctuations and ionospheric F-region activity. The correlations between the three indices were also examined and there was sufficient correlation to indicate a common origin of the fluctuations. Upon comparing the signals received at the two aerials spaced 300 metres apart it was found that the two records were similar, but not perfectly correlated. This indicated that the cause of the fluctuations had to be much larger than 300 metres. Records were compared with measurements at Dover Heights (~30km distant) and these showed almost no correlation. This suggested the source must be greater than 0.3 km, but less than 30 km in size. Based on this evidence Mills and Thomas concluded that the source of the fluctuations was irregularities from ~5 to 100 km across in the F-region of the ionosphere.

The observations of the Cygnus A source were the last that Mills made at Potts Hill until he returned in 1953 to test the prototype for the Mills Cross prior to its full-scale construction at the Fleurs field station. The experience Mills gained in using the swept-lobe interferometer configured in its static lobe mode whet his appetite for further source investigations. The low frequency (97 MHz) of the observations presented issues for accurate position estimation and Mills determined that investigations at higher frequencies should be carried out and also with longer baselines. He decided to build a dedicated instrument for these investigations rather than relying on borrowing observing time on the solar instruments. He was also concerned by the increasing radio interference at the Potts Hill site (Mills, 1984: 149) and so he determined to build his new interferometer at a new site at Badgerys Creek, a CSIRO cattle research station some 30 km to the west of Potts Hill. In 1952 he published an updated and refined position for Cygnus A as part of an investigation of the positions of six discrete sources (Mills, 1952b). In the intervening time since his first investigation he had returned to the idea that the original faint nebula he had observed was in fact the source. Unfortunately the position uncertainty was still roughly twice as large as Smith’s (1951) claimed ±1 second error and therefore the credit would go to Smith. Figure 142 shows Mills’ updated position estimate for Cygnus A, that now included the position of the faint extra-galactic nebula. This should be compared to the original estimate given in Figure 140.
Figure 142: Position estimate for Cygnus-A with position of faint extra-galactic nebula shown (Mills, 1952b: 460).

Figure 143 shows a plot of the Mills and Thomas’s original position estimate, Mills’ later position and that of Smith (1951), together with the identified galaxy position. There was some confusion in the original galaxy position used by Mills and Thomas (marked B in Figure 143) as it was in error and hence fell within their original error estimates, but the actual nebulae was in fact just outside of this tolerance (marked C in Figure 143). Note the close proximity of Smith’s position (marked D in Figure 143) and Mills’ updated position (Marked E in Figure 143).

Figure 143: Plot of Position (1950) estimates for Cygnus A. (A) = Mills and Thomas (1951) radio position. (B) = The optical position of the nebulae (in error) suggested by Mills in letter to Minkowski. (C) = actual position of nebulae. (D) = Smith (1951) radio position. (E) = Mills (1951) revised position. The square markers indicate the error estimate on Mills’ and Thomas’ (1951) radio position.

The next investigation at Potts Hill of the Cygnus source was by Piddington and Minnett as part of a broader investigation they were making at 1,210 and 3,000 MHz using the ex-Georges Height 16-ft × 18-ft
Paraboloid (Piddington and Minnett, 1952). This instrument’s primary role had been solar investigations, but like Mills and Thomas, Piddington and Minnett were able to borrow the instrument and to use it for cosmic source investigations. Originally Piddington and Minnett commenced observations at Dover Heights (Christiansen, 1950a), but soon shifted their operations to Potts Hill when the opportunity arose to use the 16-ft × 18-ft Paraboloid.

The resolution of the 16-ft × 18-ft Paraboloid was not sufficient to be useful for precise positional observations. Rather, the purpose of the observations had been to understand the broader disposition of sources at higher frequencies at 1,210 and 3,000 MHz. Piddington and Minnett noted the detection of a new discrete, but diffuse source near Cygnus A which they designated Cygnus X. They claimed in their published paper that it may be the first ‘radio nebula’ to be recognised. Due to the limited sensitivity of the equipment used at 3,000 MHz (the smaller 68-in parabola), Piddington and Minnett were unable to detect either of the Cygnus sources. Therefore they could only establish an upper limit for the flux density at 3,000 MHz. Figure 3 shows an example of the records of both the Cygnus A and Cygnus X sources during observing runs at 1,210 MHz for three different declinations.

![Figure 144](image_url)

Figure 144: Example of 1,210 MHz records of Cygnus A and Cygnus X for three different declinations (after Piddington and Minnett, 1952: 18).

By making a number of observations from declinations 36° to 47° north, they were able to construct a set of intensity contours, and given the characteristic of the aerial beam, derive the flux density of the sources as shown in lower half of Figure 145. The flux density (S) is given by:
\[ S = \frac{8\pi kT_a}{G \lambda^2} \]  

(9)

where

- \( G \) is the power gain of the aerial compared with an isotropic radiator;
- \( T_a \) is the aerial temperature;
- \( k \) is Boltzmann’s constant; and
- \( \lambda \) is the wavelength.

The estimated minimum flux density that could be detected using the 16-ft\( \times \)18-ft Paraboloid operating at 1,210 MHz was approximately \( 10^{-24} \text{W/m}^2 \text{Hz}^{-1} \) (100 Jy). For the 68-in Parabola operating at 3,000 MHz this was \( 10^{-23} \text{W/m}^2 \text{Hz}^{-1} \) (1,000 Jy).

![Image](image_url)

Figure 145: Upper graph shows contours of equal aerial beam temperature at 1,210 MHz. Lower chart shows the derived flux density of the sources Cygnus A and X (after Piddington and Minnett, 1952: 19).

The position estimates for the two sources were given as:

Cygnus-A: R.A. 19 hr. 58 min. ±2 min. \hspace{1cm} Dec. 40° 30’ ±1°
Cygnus-X: R.A. 20 hr. 27 min. ±3 min. \hspace{1cm} Dec. 40° 30’ ±1°
Given the large error tolerance, the position of Cygnus A was in general agreement with earlier estimates. Piddington and Minnett noted that the proximity of the large diffuse source to the discrete source may be the reason for the position errors in earlier interferometry measurements due to source confusion. The size of the Cygnus X source was too large to cause an interference pattern at the spacing used and hence it would have remained undetected. However, it may have contributed unseen confusion to the discrete source, particularly in right ascension.

Going back through the published observations of Cygnus A shows that the Cygnus X source did not appear in the 64 MHz observations of Hey, Parsons and Phillips (1946). However, a second source was present in Reber’s (1948) observations at 460 MHz. Reber noted that the Cygnus source had two components with very different intensity distributions as shown in Figure 146. It is interesting to note that he also concluded that interferometry would be insensitive to the measurement of this diffuse source.

Bolton and Westfold (1950b) interpreted the double source detected by Reber as being due to the general galactic background radiation as deduced from their Dover Heights sea-interferometer measurements shown in Figure 147. They concluded that rather than there being a second source, Reber had detected the extended background galactic radiation.
Figure 147: The Cygnus source interference pattern from the Dover Heights 100 MHz sea-interferometer. The record was interpreted as showing an interference pattern from the discrete source in Cygnus superimposed on the local diffuse maximum in galactic noise (after Bolton and Westfold, 1950a: 24).

Piddington and Minnett’s observations were consistent with those of Reber with the only exception being that the orientation of the extended source that Reber observed (Figure 148) appeared to be perpendicular to that observed by Piddington and Minnett. No explanation for this discrepancy was proposed other than noting the source was near the limit of Reber’s survey.
By drawing on the past observations over a range of frequencies, Piddington and Minnett were able to examine the spectra of the two sources. These spectra were then compared with the spectrum of the general galactic background radiation. Using this comparison it was possible to show that it was unlikely that Cygnus X was part of the extended background. Rather, it appeared that Cygnus X was a separate extended source with a spectrum consistent with thermal radiation from a cloud of ionised gas. The comparison of spectra is shown in Figure 149.
Figure 149: The radio spectra of Cygnus A and Cygnus X with comparison spectrums of the general galactic radiation and radiation from a theoretical gas cloud. Note that the value of flux densities for Cygnus A have been multiplied by 10 to avoid overlapping the curves (after Piddington and Minnett, 1952: 22).

The theoretical model of the gas cloud was based on a number of assumptions. The average brightness temperature ($T_b$) of a diffuse source is given by:

$$T_b = \frac{S \lambda^2}{2k\Omega} \quad (10)$$

where

$S$ is the observed flux density;
\[ \lambda \] is the wavelength;
\[ k \] is Boltzmann’s constant; and
\[ \Omega \] is the solid angle subtended.

Based on Figure 145, the solid angle subtended is approximately \( 5 \times 10^{-3} \) steradians and would give a brightness temperature of 40 K at 1,210 MHz using the above formula. The spectrum curve for Cygnus-X is consistent with thermal radiation from ionised gas with an average optical depth (\( \tau \)) of \( 3.4 \times 10^{-3} \) at 1,210 MHz. The electron temperature (\( T_e \)) of the gas is related to the brightness temperature (\( T_b \)) by the following equation:

\[ T_s = T_b (1 - e^{-\tau}) \]  \hspace{1cm} (11)

Using the assumed optical depth and the estimated brightness temperature, an electron temperature of \( 1.2 \times 10^4 \) K is the result. This temperature was in general agreement with values determined by optical observation for HII regions at the time (e.g. Stromgren, 1948).

Piddington and Minnett proposed a tentative identification of the Cygnus X source with the bright galactic nebulae surrounding the star γ Cygni. Figure 150 shows a star chart of the region with HII regions surrounding γ Cygni. It also shows the relationship to Cygnus A.
Figure 150: Star chart showing HII regions around γ Cygni. The near vertical grid lines are 1 degree declination lines. The diagonal line in the bottom right indicates the Galactic Plane. Cygnus A is marked by the cross hair (Courtesy of TheSky © Astronomy Software 1984-1998).

Piddington and Minnett noted that γ Cygni, being a spectral type F8p, was unlikely to be the sole source of excitation of the HII region and that other obscured O and B spectral class stars may be responsible. We know today that the Cygnus X region is one of the largest star-forming regions in our Galaxy with many OB stars in a coherent molecular cloud that is at a distance of ~1.7 kpc (Schneider et al., 2006).

Piddington and Minnett’s program of cosmic observation had begun in 1948 with some preliminary observations of the region of the Galactic Centre using a 10-ft Parabola at 1,210 MHz. Later the opportunity arose to use the larger 16-ft × 18 ft Paraboloid and the 68-in Parabola. They used these for the Cygnus observations (discussed above) and for observations of the Galactic Centre, Taurus A (the Crab Nebula), Centaurus A, the Moon, M31 (the Andromeda Nebula and NGC 7293 (a large planetary nebula). The results of these observations were published in the Australian Journal of Scientific Research (Piddington and Minnett, 1951a). This was an important historical paper because it included the discovery of the discrete radio source at the Galactic centre now known as Sagittarius A. As discussed by Goss and McGee (1996) and Orchiston and Slee (2002) there are many misconceptions related to the discovery of Sagittarius A. Credit is often incorrectly given (e.g. Kerr, 1983: 297) to McGee and Bolton, who in a paper

Since Jansky’s original discovery (1933), the coincidence of the maximum level of radio emission with the centre of our Galaxy had been noted. Examples of early surveys by Reber (1944, 1948), Hey, Parsons and Phillips (1946), and Bolton and Westfold (1950a,b) all showed the maximum originating near the position R.A. 17 hr. 50 min., 27°S. Figure 151 shows a summary of these early surveys converted to common projections. Apart from the survey by Hey, Parson and Phillips, which shows an unexplained complex structure, there is similarly between the surveys at the different frequencies.

![Figure 151: Examples of earlier surveys around the Galactic Centre (Bolton and Westfold, 1950b: 255).](image-url)
Piddington and Minnett’s survey at 1,210 MHz was made by taking a number of drift scans at different declinations spaced approximately 1 degree apart. Figure 152 shows an example of a single scan where Sagittarius A is very apparent.

Figure 152: Example of a drift scan at 1,210 MHz across the Galactic Plane and showing the discrete source Sagittarius A. The beam width was ±1.4°. Note that the original caption published with this figure incorrectly referred to the beam width of the 68-in Parabola that was used for the 3,000 MHz observations (Piddington and Minnett, 1951a: 463).

Based on the continuous recording of aerial temperature during the drift scan, the records were reduced to a set of equal intensity contours as shown in Figure 153.
Based on the contour map, Piddington and Minnett announced:

“An examination of these contours reveals several points of interest. Firstly, the sharp maximum at R.A. 17 hr 44 min., Dec 30°S. appears to be a new, and remarkably powerful, discrete source. Secondly, the contours provide another determination of the position of the galactic centre. Finally the results allow a determination to be made of the excess radiation from near the galactic centre (above an unknown, but probably low, level away from the galactic plane).” (Piddington and Minnett, 1951a: 465).

Although certainly not as clearly stated as the later papers by McGee and Bolton (1954) and McGee, Slee and Stanley (1955), Piddington and Minnett do make the association of the new source with the Galactic Centre. The minutes of the Radio Astronomy Committee of February 6, 1949 also reported the discovery of “a new discrete source” found in the region of the galactic centre (Christiansen, 1951b). It is interesting that it would take nearly three years after formal publication before this association was more closely examined and the exciting linkage to the Galactic Nucleus was more clearly established. The Dover Height 80-ft hole-in-the-ground parabola was able to achieve an angular resolution in the order of 1° at 400 MHz, and with a much more sensitive receiver, the position and angular size of Sagittarius A was defined with greater accuracy.

The 3,000 MHz equipment was operating at its limits and the combination of instrument noise and receiver drift made it difficult to obtain useful results. A beam swinging technique was adapted to improve sensitivity and Piddington and Minnett were able to estimate the excess brightness temperature near the Galactic Centre. They estimated this to be 2.6 K with a 20% uncertainty. At 1,210 MHz they estimated the brightness temperature to be 17 K with a 20% uncertainty.
With a beamwidth of 1.4° the accuracy of the position of the new discrete source was estimated to have an uncertainty of 2 minutes in R.A. and approximately 1° in Declination. From the transit time of the source through the aerial beam it was estimated that the source must be smaller than 1.5° in diameter. The calculated flux density for the source at 1,210 MHz was $2.6 \times 10^{-23} \text{W.m}^{-2} \text{Hz}^{-1}$. Given the coincidence of the source with the Galactic Centre, Piddington and Minnett concluded that the source must be extremely powerful. Assuming a distance of $10^4$ parsec the source radiation in the radio spectrum alone would be at least 100 times greater than the total power radiated by the Sun.

Piddington and Minnett also make reference to personal communication with Mills prior to publishing their results. Mills was conducting a source survey at 100 MHz at the Badgerys Creek field station using an interferometer with spacings of 270m and 60m (Mills, 1952b). They noted that Mills had also detected a source at about R.A. 17 hr. 50 min., Dec 28.5°S. with a very approximate flux density of $3 \times 10^{-23} \text{W.m}^{-2} \text{Hz}^{-1}$ (source 17-2B in Mills, 1952a: 286) and concluded that despite the position difference, this was very likely to be the same discrete source. No reference was made to the source size. The interferometer measurement indicated a source size of 35 arc minutes. In the final published catalogue Mills listed the flux density as being one order of magnitude lower than had first been suggested. Observations were also obtained from Shain who was observing at 18.3 MHz at the Hornsby Valley field station and these gave a flux density measure of $3 \times 10^{-24} \text{W.m}^{-2} \text{Hz}^{-1}$ with an uncertainty of not worse than 50 percent. Using these data Piddington and Minnett were able to obtain a preliminary spectrum of the source. Figure 154 shows this spectrum, together with an example of two other known discrete sources, Taurus A and Centaurus A.
Figure 154: The radio spectra for the discrete sources Sagittarius A, Centaurus A and Taurus A. The flux density scale for Taurus A has been changed by a factor of 10 to separate the curves (after Piddington and Minnett, 1951a: 468).

Although noting that a spectrum based on three data points was tentative, Piddington and Minnett suggested the spectrum resembled that of an optically thin, thermally radiating gas, but also had some characteristics similar to that of the Taurus-A spectrum. Although Alfvén and Herlofson’s paper (1950) suggesting synchrotron radiation as the possible mechanism for extragalactic radio emission had been published at this time, it was not until further work on Taurus-A and the verification of polarised light by Dombrovsky (1954) that this emission mechanism gained more general acceptance. Piddington and Minnett noted from their observations of Taurus A that when the electron temperature and density were calculated based on the radio observations there was a very large discrepancy compared to the optical data if thermal radiation was assumed. This suggested a possible non-thermal origin, but the spectrum could not be reconciled with the other non-thermal mechanisms known at the time.

Piddington and Minnett (1951a) investigated three other known discrete sources. However, only Centaurus A could be detected at 1,210 MHz with a flux density of $4.1 \times 10^{-24}$ W.m$^{-2}$.Hz$^{-1}$ and an uncertainty of 20 percent. The two other sources investigated, Virgo A and Hercules A, could not be
detected and therefore it was assumed their flux densities were less than $1 \times 10^{-24}$ W.m$^{-2}$.Hz$^{-1}$. No attempt was made to observe these sources at 3,000 MHz.

Attempts were also made to detect M31 and the large planetary nebula NGC 7293 (ibid.). Neither of these sources could be detected at 1,210 or 3,000 MHz. Subsequent to the observations, but prior to publication, Hanbury-Brown and Hazard (1950) detected radiation from M31 at 158 MHz with an observed flux density of $4 \times 10^{-24}$ W.m$^{-2}$.Hz$^{-1}$. Piddington and Minnett noted that if the spectrum of M31 was similar to our own Galaxy then the flux density at 1,210 MHz would be $2 \times 10^{-24}$ W.m$^{-2}$.Hz$^{-1}$, which was below the detection threshold of the equipment they were using.

As a form of calibration test, Piddington and Minnett also observed the Moon and compared these observations to their earlier observations at 24,000 MHz (1949a). The apparent disk temperatures were broadly in-line, although slightly higher, than those obtained at the higher frequency.

In January 1955, as part of a joint project between the URSI and Commission 40 of the I.A.U., a catalogue of reliably-known discrete radio sources was published (Pawsey, 1955a). The catalogue was prepared in early 1954 based on surveys that had been published up to that time. This catalogue provides a good guide to the state of investigation of discrete sources in this period. A total of 38 sources was listed in the catalogue. Of these, only 8 sources were definitively established, with accurate positions determined by a number of independent observers and optical identifications obtained. The remaining 30 sources were included in the catalogue on the basis that there was reasonable agreement of the source positions from at least two independent observations. Of these, 9 had reasonable identification candidates proposed. Included in this list were both Sagittarius A and Cygnus X. These sources had first been proposed by Piddington and Minnett based on their Potts Hill observations. Thus, using Pawsey’s (1955a) review as an objective measure, as at 1954 five percent of all known discrete radio sources had been determined based on research at Potts Hill.

The 1,210 MHz cosmic survey work by Piddington and Minnett was to be the last major program of observations using the 16-ft × 18-ft Paraboloid. Having originally been designed as an experimental radar, it was far from ideal as a survey radio telescope. It suffered from sagging and distortion of the reflector surface and the multiple dipoles at the prime focus caused further losses in sensitivity (see Piddington and Trent, 1956b: 490n).

The construction of the 36-ft Transit Parabola for H-line survey work presented a new opportunity. Piddington and Trent modified the receiver design that had been used at 1,210 MHz on the 16-ft × 18-ft Paraboloid to operate at 600 MHz, and, together with a 6-ft Parabola operating as the reference aerial, they used the 36-ft Transit Parabola for a survey at 600 MHz covering the declination range 90°S to 51°N.
The reason for selecting 600 MHz was because surveys of the southern sky had already been conducted at 100 MHz (Bolton and Westfold, 1950a) and 200 MHz (Allen and Gum, 1950). Instruments used for both of these surveys had low resolution, namely beamwidths of 17° and 25° respectively. Bracewell and Roberts (1954) had shown that all detail within an aerial beam could not be subsequently recovered by either graphical or other processing techniques and therefore is lost. This meant that the plots of brightness distribution, particularly in the area of the Galactic Plane, could not be even approximately accurate in terms of source structures. Piddington and Trent determined therefore to conduct a much higher-resolution survey using a pencil-beam instrument. The 36-ft Transit Parabola operating at 600 MHz had a beamwidth of 3.3°.

The observations from the survey were reduced to a measure of aerial beam temperatures from which a contour plot of isophotes was produced. The aerial beam temperature was calculated by considering that two-thirds of the total energy received would be in the main beam of the aerial with the remainder in the side-lobes. Assuming that the main beam was placed on a source of a given temperature \( T \) and the side lobes were directed at zero temperature regions, the aerial temperature \( T_a \) was given by:

\[
T_a = \frac{2}{3} T
\]

Therefore, in the ideal case, the aerial beam temperature was \( \frac{3}{2} \) times the measured aerial temperature. In practice many other factors such as ground reflection and the background radiation within the side lobes complicated this calculation. However, for the beamwidth and frequencies involved these errors were likely to be less than 10 percent. For the 600 MHz survey Piddington and Trent multiplied the measured aerial temperature by a factor of \( \frac{100}{65} \) to obtain the aerial beam temperature.

The aerial temperature is not an absolute measure; rather it is a measure above a minimum background level. To obtain an estimate of the actual temperature it is necessary to determine the minimum background temperature at a given frequency. Piddington and Trent used the best available measurements from earlier surveys to construct the radio spectrum curve shown in Figure 155.
By extrapolating this curve to 600 MHz an estimate of the background temperature could be obtained. From Figure 155 the brightness at 600 MHz was $4.5 \times 10^{-22} \text{W.m}^{-2} \text{Hz}^{-1}$ which corresponds to a brightness temperature of 4 °K. From their survey measurement they calculated the base level of the minimum background ranged from 4 to 8 °K, with an average value of 5.7 °K.

The results of the full survey are shown in Figure 156. The main features of the survey were the strong source Sagittarius-A which had been associated with the Galactic Centre, the two sources in Cygnus, Cygnus-A and Cygnus-X, Centaurus-A, and Taurus-A the Crab Nebula. There was also a string of sources on or near the galactic plane which Piddington and Trent proposed were likely to be related to thermally emitting HII regions. For comparison, Figure 157 shows a much later survey at 408 MHz (Haslam et al., 1982) for the equivalent region in Figure 157. The degree of detail in the 600 MHz survey is remarkable for its time, particularly given the receiver limitations in this era.
Figure 156: The 600 MHz survey showing contours based on aerial beam temperature (Piddington and Trent, 1956b).

Figure 157: A more recent 408 MHz survey showing the equivalent region to the 600 MHz survey (after Haslam et al., 1982).
By the mid 1950’s the synchrotron process as a source of galactic radio emission had become fairly well accepted (Piddington and Trent, 1956b: 489). Piddington and Trent observed that thermal emission from ionized hydrogen still remained a major component of the observed radiation, just as Piddington (1951) had earlier suggested. They proposed that the observations were consistent with a model of synchrotron emission constituting a single spheroidal system with a variable emission per unit volume that increased towards the Galactic Plane where thermal radiation was also concentrated. They concluded that the galactic concentration of thermal emission was consistent with the broad HII distribution of the Galaxy.

As part of the survey Piddington and Trent also noted that because of the higher frequency and narrow beam width, it was possible to make a useful re-determination of the Galactic Equator and also the position of the Sun above the Equator. Figure 158 shows the position of the ridge of maximum intensity of the radio emission plotted in galactic coordinates.

![Figure 158: The position of the ridge of maximum radio emission at 600 MHz plotted in galactic coordinates. The dotted line represents a hypothetical galaxy model. 242 MHz observations near the Galactic Pole are also shown (after Piddington and Trent, 1956b: 491).](image-url)

By assuming the Galaxy is circularly symmetrical with a diameter of 19,000 parsec and that the Sun is 1,600 parsecs from the outer edge, a theoretical curve of the Galactic Equator was determined. This is shown as the dotted line in Figure 158. The best fit was given by assuming a radio pole lying at $b = 89.0^\circ$ and $l = 330^\circ$. Included in the plot are measurements at 242 MHz taken by Ko and Krauss of Ohio State University. These data favour a value of $b = 89.1^\circ$. The corresponding position of the Sun above the Equator is 42 parsec, while the 242 MHz data give 56 parsec. Earlier calculations based on optical
observations (van Tulder, 1942) had shown a smaller solar displacement of 13.5 parsecs, but that was in the same direction.

Piddington and Tent separately published a catalogue of 49 sources based on the 600 MHz survey (1956a). Of these sources, 31 appear to have been identified in previous radio surveys, with the remaining 18 being newly identified sources. Of these 18 sources, 12 were located within ±2° of the Galactic Plane. For 4 of the sources optical identifications were proposed, all of these being with HII regions. No optical associations were proposed for the remaining 14 radio sources. Figure 159 shows the variation of emission intensity by galactic longitude with the individual sources within a few degrees of the Galactic Plane individually marked. The numbers refer to the source numbers in the published catalogue.

![Figure 159: Variation of intensity at 600 MHz along the Galactic Plane. Individual sources, marked with their catalogue number are shown. Source 37 is Sagittarius A (after Piddington and Tent, 1956a: 81).](image)

A key conclusion of the examination of the sources was that many of those lying close to the Galactic Plane rather than being discrete sources appeared to have more complex structures and were often more akin to local maxima. Earlier interferometer surveys assumed many of these sources were discrete. The interferometers were unable to detect extended sources and their position estimates were confusion affected, as appeared to be the case for the later Cambridge 2C survey (Mills and Slee, 1957).

With the 36-ft Transit Parabola no longer being used for the H-line survey, Hindman and Wade modified the H-line receiver to measure the general radio continuum at 1,400 MHz rather than H-line emission. They used the modified equipment to observe a number of sources, but only published their
observations of the Eta Carinae Nebula (NGC 3372) and Centaurus A (NGC 5128) (Hindman and Wade, 1959).

Eta Carinae was targeted because little was known of its physical properties. It was also the only important galactic HII emission nebula that had not been covered by Westerhout’s (1958) 1.390 MHz survey because it was located too far south to be visible from the Netherlands. A series of drift scans of the nebula were taken as illustrated in Figure 160. From these a set of contour diagrams of aerial temperature as a function of position was produced, as shown in Figure 161.

Figure 160: Example of a drift scan through the Eta Carinae Nebula (NGC 3372) (after Hindman and Wade, 1959: 262).
By correcting for the background galactic radiation and integrating over the contours, Hindman and Wade were able to determine a value of $5.82 \times 10^{-24}$ Wm$^{-2}$ Hz$^{-1}$ for the flux density of the Eta Carinae Nebula, with a probable error of $< 20\%$. They also noted that there appeared to be no large-scale asymmetry to the surface brightness distribution of the source and that the source appeared to be strongly concentrated towards its centre.

In a separate paper, Wade (1959a) examined a physical model of the Nebula based on the Potts Hill observations and also drawing on the flux density measurement at 85.5 MHz (Mills et al., 1956) and some unpublished optical measurements that had been made by Gum. Figure 162 shows the line along which Gum had measured the H$\alpha$ surface brightness of the Nebula.
Wade’s findings were largely consistent with previous studies on emission nebulae, confirming that the radio emission could be explained solely by the thermal mechanism of free-free transitions. Wade found that a relatively simple model of the emission nebula having a spherical distribution with an electron temperature of $10,000 \pm 1,000$ K, a dense core and a broad tenuous envelope, could provide a good account of both the radio and optical observations. Figure 163 illustrates the derived model.
Assuming a distance to the Nebula of 1,400 parsecs yielded an r.m.s. density of 71 ions cm$^{-3}$ for the core and 11 ions cm$^{-3}$ in the outer regions of the Nebula. This meant that the total mass on the nebula was not more than 25,000 solar masses. Wade also showed that it was likely that several O class stars would be needed to maintain the observed ionization of the Nebula.

The other source observed at 1,400 MHz by Hindman and Wade (1959) was Centaurus A. Their findings were largely similar to the conclusions reached from earlier interferometric measurements (Bolton et al., 1954; Mills, 1953) and confirmed by later pencil beam measurements at 19.7 MHz (Shain, 1958) and 85.5 MHz (Sheridan, 1958). They found that the source was composed of two components. One of these was a localised discrete source associated with the optical galaxy NGC 5128. The second component was a large extended source with no optical counterpart. Figure 164 shows the contour map of aerial temperature for Centaurus A.

![Contour map of aerial temperature for Centaurus A at 1,400 MHz. The dotted lines are estimates of the contour lines which were below the detection threshold of the equipment (after Hindman and Wade, 1959: 268).](image)
The derived flux density of Centaurus A was calculated as $1.3 \times 10^{-24} \text{ Wm}^{-2} \text{ Hz}^{-1}$ ±20 percent, with 23 percent of the radiation coming from the point source and the remainder from the extended source. Although no new findings were made in these observations they provided additional data at previously-unobserved frequencies. Wade (1959b) subsequently published a summary of the radio observations of Centaurus A, including the 1,400 MHz Potts Hill observations, noting the similarity of the contour diagrams across the different frequencies.

Apart from the Eta Carina Nebula and Centaurus A, Hindman and Wade also used the Potts Hill 36-ft Transit Parabola to observe continuum emission from Sagittarius A at 1,400 MHz, but for some reason they never published their observation (see Gum and Pawsey, 1960: 158).

The 1,400 MHz continuum investigations by Hindman and Wade were the last investigations made at Potts Hill using the 36-ft Transit Parabola.

### 10.5.2.2. H-line Investigations

Nearly all of the early major discoveries in radio astronomy, including Jansky’s original detection of cosmic radio emissions, were serendipitous. Serendipitous discoveries in radio astronomy have been well discussed in the literature (e.g. Kellermann, 1983). Perhaps the best example of an exception to this phenomenon was the discovery of the 21 cm Hydrogen emission line. As Sullivan has noted (1982: 299), the predication was remarkable on two counts; both for its scientific prescience and for the conditions under which it was produced. Van de Hulst was a graduate student at the time of the Nazi occupation of Holland and his supervisor from Utrecht University had been interned. Van de Hulst spent three months visiting Leiden (van Woerden and Strom, 2006: 17, Note 2), where under Oort’s guidance he examined the possibility of discrete emission from neutral hydrogen. In a paper published immediately after the war ended, van de Hulst cautiously noted the possibility of detecting an emission line:

“The ground state of hydrogen is split by hyperfine structure into two levels with a separation of 0.047 cm$^{-1}$. The spins of the electron and proton are pointed in the same direction in one state and are opposite in the other state. A quantum of wavelength 21.2 cm is emitted due to a spontaneous flip of the spin.” (van de Hulst, 1945).

Van de Hulst noted that the transition to ground state was a forbidden transition and therefore it was necessary to assume a probability for the spontaneous transition to the preferred ground state. Provided that the life time of the hydrogen atom in the upper hyperfine-structure level was less than $4 \times 10^8$ years, there was a possibility of detection. He also noted that the sensitivity of radio receivers would need to be improved by a factor of 100 over the 1940s levels of equipment for the emission to be detected.
The actual value of the emission frequency from the spin flip transition to the ground state is 1,420.4 MHz ($\lambda = 21.1 $ cm) and is due to the hyperfine structure transition being $5.9 \times 10^{-6}$ eV (Wild, 1952). This is an extremely small energy level when compared for example with the Lyman-alpha transition of 10.19 eV which produces an emission at the much shorter wavelength of 122 nm. The probability of transition to the ground state is $2.9 \times 10^{-15}$ sec$^{-1}$ ($\sim 10^7$ years), and is within van de Hulst’s original limit. In 1947 the hyperfine structure of both atomic hydrogen and deuterium was experimentally measured using atomic-beam magnetic resonance at the Columbia University Radiation Laboratory under the supervision of I.I. Rabi (Nafe and Nelson, 1948; Nafe et al., 1947).

It is interesting to note that Pawsey was well aware of the potential that detecting radio spectral lines would provide to radio astronomy. He was also familiar with the predicted 1,420.47 MHz Hydrogen emission and also the prediction of Deuterium emission at 237.38 MHz. It was Reber who first alerted Pawsey to the theoretical predictions and to the possibilities of detection during a visit by the latter to the U.S. in early 1948. Reber had met van de Hulst in 1945 (Reber, 1984: 64) and subsequently promoted the possibility of detection the H-line in emission (see Reber and Greenstein, 1947: 19). Given the important implications that the detection of a radio-frequency spectral line would bring to radio astronomy, Pawsey alerted Bowen to this potential in a letter dated 23 January 1948. Pawsey also included a section titled, “The Search for Atomic Spectral Lines in Noise”, in the trip report he wrote following his visit to the United States. After a discussion of the potential he concluded:

“The position is therefore quite uncertain. Lamb of Columbia, for example, did not expect we should be able to find lines owing to low probabilities of emission or absorption and “smearing”, due to changes due to magnetic fields and so on.” (Pawsey, 1948d).

During his U.S. visit Pawsey also visited Harvard and met Oort who was visiting Yerkes Observatory at the time. However, there is no mention of any discussion on the H-line potential with these parties.

Bowen responded to Pawsey’s U.S. visit report in a letter dated 18 May 1948, where he noted:

“This [atomic spectral lines] possibility is certainly an interesting one but, in view of the present state of knowledge, I doubt very much whether we should yet devote a special effort to it. A search for the atomic hydrogen and deuterium lines could be made with the Georges Heights equipment but this would involve dislocation of other work which is scarcely justified at present. At the moment Harry Minnett is chasing up the references you supplied and we are hoping that Williamson will live up to the promise he made you to let us have a survey of the whole subject.” (Bowen, 1948a).
The report from Pawsey triggered some activity at Radiophysics. In early 1949, Wild produced an internal report titled, “The Radio-Frequency Line-Spectrum of Atomic Hydrogen. I. The Calculation of Frequencies of Possible Transmissions”. This report was a comprehensive survey of the earlier theoretical work on the subject and Bowen noted in a letter to F.W.G. White (Chief Executive Officer of the C.S.I.R.O.) on 21 March 1949:

“There is nothing very original about it but it serves to indicate the direction in which his work might go.” (Bowen, 1949).

White replied to Bowen’s on 28 March 1949 and noted:

“I have looked through it [the report] and find that, even to one who is not a spectroscopist, it is relatively easy to follow. The end results are certainly very interesting, and I hope that experimental data can now be found to which these can be related.” (White, 1949).

As Sullivan (2005: 14) has reported, in 1949 Mills had considered taking on the H-line search as an independent line of research, but dismissed it as too speculative. Mills himself recalled that Pawsey had presented him with the choice of attempting to detect the H-line or investigating discrete sources using the Swept-Lobe Interferometer:

“If I had been a trained astronomer and therefore aware of the possible great importance of the H line no doubt this would have been my choice...” (Mills, 2006: 2)

Bolton and Westfold had also considered searching for the H-line (Robertson, 1992: 82). They had a copy of a Russian paper (Shklovsky, 1949) translated in an effort to obtain more details, however no search was undertaken. Murray (2007) has also recalled that Payne-Scott proposed a search for the H-line on a number of occasions at meetings of the solar noise group, although no record appears in the minutes.

Despite this early insight, there was no detection attempt by the Radiophysics Group. As late as February 1951, in a meeting of the Radio Astronomy Sub-Committee on Galactic Work, Shain raised the possibility of looking for line spectra as part of the Group’s research efforts. In attendance at this meeting were Pawsey, Bolton, Mills, Minnett, Piddington and Shain. The outcome was recorded in the minutes:

“It was decided, however, not to plan for this as it could be easily fitted into other projects.” (Mills, 1951b).

On 25 March 1951, H.I. Ewen, who was working on his Doctoral thesis at the Lyman Laboratory at Harvard University detected the 21-cm emission line (Ewen and Purcell, 1951). In a remarkable
coincidence, van de Hulst was visiting Harvard at the time and discussed the detection with Ewen and his supervisor E.M. Purcell. Van de Hulst indicated that the Dutch group under Oort and Muller had been attempting to detect the H-line for some time. By Ewen’s own account (2003) he was unaware of the Dutch group’s work and had dismissed the possibility of the Dutch actively pursuing a detection attempt because he had interpreted van de Hulst’s comments in his original paper as indicating that a detection was highly unlikely. In fact, Ewen thought it likely that his thesis would indicate a negative result. Ewen believed that if any group would undertake a detection attempt it would be from the Soviet Union on the basis of Shklovsky’s independent prediction (1949), with which Ewen was familiar.

Also visiting Harvard University at this time was Kerr from the Radiophysics Laboratory in Sydney (Kerr, 1984: 137). Kerr was on a fellowship to Harvard to undertake studies in astronomy at the Harvard College Observatory under Dr. H. Menzel. Kerr had written to Pawsey on 17 March 1951 drawing to his attention the fact that two groups had already made unsuccessful attempts to detect the H-line (Kerr, 1951). At this time Ewen had still been unsuccessful and Owren at Cornell University, who was using an 8-ft Parabola and a receiver similar to Ewen’s but with less sensitivity, had also been unsuccessful. On making the initial discovery Purcell and Ewen shared details of the discovery with the Dutch group and were keen to obtain an independent confirmation of the detection. Kerr sent Pawsey an airmail letter on 30 March 1951 alerting him to the discovery and asking if the Sydney group could assist in the confirmation, even though no prior work had been conducted by Sydney. The letter included a hand-drawn sketch of the H-line response on Ewen’s receiver (Figure 165). In a letter dated 20 April 1951, Pawsey wrote to Purcell saying that because of the “...great potentialities...” he had assigned two separate groups to attempt the independent detection and they were optimistically hoping to get results “...in a few weeks”. He also enquired as to the processes that would be used for publication of the discovery and suggested that they would privately communicate any detection and then publish a confirmation note at the time Ewen and Purcell decided to publish their result.

In his letter to Purcell, Pawsey referred to two independent groups working on attempting a confirmation. A meeting was held on 12 April to coordinate the activities of the Radiophysics Group in attempting a confirmation observation. In attendance at this meeting were Pawsey, Higgs, Piddington, Christiansen, Wild and Bolton. The minutes recorded:

“It was agreed that parallel investigations to check detectability of lines were desirable in order to obtain independent checks but that, in order to avoid cut-throat competition, the groups who were experimenting in the same field, e.g. Piddington, Christiansen and Wild, should consider themselves, at least on the 1420 Mc/s line, as a single group and possible publication should be joint.

Wild outlined the theoretical results he had obtained (mainly in RPL. 33 and 34). The chief point of interest is the existence of fine-structure lines at 10,905, 3,231 & 1,363 Mc/s with “inherent” line widths of the order of 100 and 20 Mc/s respectively.

It was agreed to recommend Wild to write up this material for publication.

Christiansen and Bolton outlined schemes for attempting to detect the 1420 Mc/s line with which they were proceeding (also corresponding deuterium line). They hope to have equipment for tests to start in a week or so.

Piddington outlined a different scheme with which he was proceeding.” (Pawsey, 1951a).

Orchiston and Slee (2005a: 139) have stated that Christiansen and Hindman worked independently at the Potts Hill field station before they discovered they had both been tasked by Pawsey to work on the same problem. This is likely a reference to the early parallel work by Piddington and Christiansen. At the time Hindman was working for Piddington. It is unlikely that they did not know about each other’s work, but rather this was a deliberate strategy as the minutes of the 12 April meeting reflect. After a short period, Christiansen took the leadership of the group with support from Hindman. It is unclear when Bolton’s detection attempts were abandoned. However, in 1953-54, an unsuccessful attempt was made by G. Stanley and R. Price at Dover Heights to detect the postulated Deuterium line.

Purcell replied to Pawsey in a letter dated 9 May 1951. He welcomed the efforts of the Sydney group and provided further details of the detection and their receiving equipment. He also indicated that they intended announcing the discovery in *Nature* “...fairly soon...”, but would allow time for a reply before proceeding. Pawsey replied in a letter dated 18 May 1951, saying that Christiansen would be, “...attempting the first observations tonight...” and that he would be away for the next fortnight and hence Christiansen would communicate directly if the attempt was successful, although he noted it would likely
take several weeks. He also suggested that Ewen may wish to publish a detailed report in the *Australian Journal of Scientific Research*.

Christiansen and Hindman were able to construct a ‘makeshift’ receiver (1952b: 438) in a very short period through a great deal of improvisation. The receiver was in principle similar to that used by Ewen, and by Muller and Oort in Holland. Coupling the receiver to the 16-ft × 18-ft Paraboloid Christiansen and Hindman were able to confirm the H-line detection. The minutes of the Radio Astronomy Committee of September 1951 record that the confirmation detection was made on 6 July 1951 (Christiansen, 1951a), only 15 weeks after the original discovery on 25 March 1951.

It is interesting to note Christiansen’s own recollection:

“We knew when we started that our gear was so rotten it mightn’t work at all. Without exaggeration it was held together with string and sealing wax; Pawsey said it kept going through sheer will power. To make matters worse sparrows kept nesting in the aerial. We were stuck out at Potts Hill reservoir and it rained like all hell all the time. After observing for 10 days, without any luck we got fed up and went home, leaving the machine switched on. The next morning we found what we were after sitting up on the chart.” (Christiansen, 1954).

Figure 166 shows an example of the H-line observation obtained by Christiansen and Hindman. This can be compared to Ewen’s original observations, an example of which is shown in Figure 167.
Ewen and Purcell’s discovery was announced in the 1 September 1951 issue of *Nature* in a letter dated 14 June 1951. It appeared together with a confirmation paper by the Dutch group (Muller and Oort, 1951) dated 26 June and a short cabled communication dated 12 July from Australia also confirming the detection of the H-line (Pawsey, 1951b).

Pawsey noted in a letter he sent to Bowen on 13 July 1951 advising of the confirmation:

“Christiansen has worked like a [deleted] for the last two months trying to get this gear working and it is a very creditable performance on his part. The line is really exceedingly weak and it is necessary to make the right compromises all along the way in order to make the spectrum line evident.” (Pawsey, 1951c).

Following the initial confirmation, between June and September 1951 Christiansen and Hindman proceeded to make a preliminary survey of hydrogen emission in the southern sky. The detailed findings of their survey were published in the *Australian Journal of Scientific Research* (Christiansen and Hindman, 1952b), and a summary paper also appeared in *The Observatory* (Christiansen and Hindman, 1952a).

By taking a series of measurements in progressive steps of right ascension they were able to obtain a series of profiles by declination. Figure 168 shows an example of a series of records taken along the Galactic Equator.
From these individual records, the maximum deflection could be measured and hence a series of brightness intensities could be calculated. Figure 169 shows an example of the profile of peak brightness for declination +10°.

By combining these profiles a contour chart of peak brightness was constructed. A peak brightness corresponding to a brightness temperature of approximately 100 K was observed. Figure 170 shows the final contour map of hydrogen-line emission. From this map it was evident there were marked variations in the peak brightness along the Galactic Equator. Christiansen and Hindman noted that there were two likely causes of these variations. The first was that the variations were due to line broadening caused by rotation of the Galaxy and the second, and more interesting possibility, was they were the result of structural features such as the spiral arms.
Figure 170: Full sky contour map of hydrogen-line emission. The peak brightness of 25 units corresponds to a brightness temperature of approximately 100 K (after Christiansen and Hindman, 1952b: 446).
The line profiles were calculated based on the receiver response in the two swept-band filters of the receiver. Figure 171 shows examples of arbitrary line profiles and their corresponding receiver outputs.

![Example line profiles and receiver outputs](image1.png)

Figure 171: Example line profiles (a) and the corresponding receiver outputs (b). The sweep (s) of the two pass-bands (black boxes) is shown in the top left (after Christiansen and Hindman, 1952b: 442).

The process of reconstruction of the line profiles from the receiver records was essentially the reverse of that shown in Figure 171. Figure 172 shows examples of the smoothed records and reconstructed line profiles for the Galactic Centre, Anti-centre and Cygnus regions.

![Smoothed records and calculated line profiles](image2.png)

Figure 172: Examples of smoothed records and the calculated line profile in the region of the Galactic Centre (a), the Anti-centre (b) and the Cygnus region (c) (after Christiansen and Hindman, 1952b: 447).
Based on the broadening of line profiles, random velocities of the order of 12 to 18 km/s were estimated to be present in the neutral hydrogen clouds. In a number of cases double line profiles were also detected, as shown in Figure 173.

![Figure 173: An example of the smoothed record and the resulting double line profile (after Christiansen and Hindman, 1952b: 448).](image)

The existence of these double line profiles indicated regions with different radial velocities. Assuming a circularly symmetrical rotating galaxy, the radial velocity \( v \) of different regions is given by:

\[
    v = r.A \sin 2l'
\]  \hspace{1cm} (13)

where
- \( r \) is the distance of the source from the Sun;
- \( A \) is \( 6 \times 10^{-16} \) sec\(^{-1}\); and
- \( l' \) is the modified galactic longitude with respect to the galactic centre.

From this equation, given a radial velocity estimate derived from the Doppler frequency shift compared to the rest frequency, a distance to the source could be estimated. The estimate for the two major regions showing double lines was 1,000 and 4,000 parsecs. Given the large size and the separation of the double lines (marked (a)) as shown in Figure 175, the structure was suggestive of spiral arms in the Galaxy.

Further evidence supporting the detection of galactic structure was found by comparing the theoretical effect of galactic rotation with the actual observations. Assuming a uniform medium producing radiation, it is possible to calculate the brightness profiles for different hydrogen densities. Figure 176 shows the theoretical plots where \((n)\) is the number of ground state hydrogen atoms per cm\(^3\).
Figure 174: Comparison of hydrogen-line emission (top) to 480 MHz, 200 MHz and 100 MHz (bottom). Structural similarities are evident (after Christiansen and Hindman, 1952b: 451).

The plot showed reasonable agreement with a density of somewhere between 1 and 0.5 atoms per cm$^3$. However, there were clearly regions where factors other than rotation were causing brightness variations. Also, by comparing the overall hydrogen emission to the general radio emission, which would not be effected by rotation, it was clear that there was general agreement between structural areas as shown in Figure 175. These factors suggested the existence of spiral arms in the Galaxy and Christiansen and Hindman concluded that a much more detailed investigation was warranted.
Figure 175: Plot of centre frequencies for line profiles showing double line profiles (a) and single line profile (b) regions. Line (c) is the expected frequency variation due to the Earth's relative motion (after Christiansen and Hindman, 1952b: 448).

Figure 176: Calculated brightness peaks due to galactic rotation for given hydrogen densities ($n$). Dots indicate actual observations (after Christiansen and Hindman, 1952b: 450).

Overall there were clear indications that the hydrogen-line emission occupied roughly the same distribution in the sky as the visible Milky Way. This association and the ability to penetrate the obscuring medium to discover galactic structure heralded the beginning of a very important branch of investigations in radio astronomy. It also marked the beginning of a major international collaboration, particularly with the Dutch group working at Leiden, and was characterised by close cooperation that started with the prepublication communications by Ewen and Purcell with both the Dutch and Australian groups.

It is ironic that in the same year that the breakthrough discovery of a radio frequency emission line occurred, the first optical evidence for spiral arm structures in our Galaxy was also published (Morgan et al., 1952; Sheehan, 2008).

Immediately following the Australian confirmation of the H-line, Wild decided to update and publish the internal report he had written prior to the detection of the H-line (Wild, 1952). This was a comprehensive review of the radio-frequency line spectrum of atomic hydrogen and is largely in accordance with modern theory. The report provided a very solid theoretical base for planning of further observations by the Australians. The one exception in this analysis was the conclusion that the 1,420 MHz
emission would be the only detectable line emission, and that it would be unlikely that the higher order recombination lines would be detectable. It would be nearly two decades before the recombination lines were detected in the Soviet Union (Sullivan, 1982: 300).

From 8-22 August 1952 the Tenth General Assembly of the International Union of Radio Science (URSI) was held in Sydney. Attending the meeting were Ewen from Harvard and Muller from Leiden. This meant that for the first time, those that had been involved in the initial detection of the Hydrogen emission were able to meet face to face (Figure 177).

At the URSI meeting this group decided to arrange a regular exchange of information by way of a regular newsletter that tracked the progress of the various groups undertaking research. The first issue of this newsletter appeared in December 1952 and was circulated to those listed in Table 4.

Table 4: H-line Newsletter Recipients

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. H.I. Ewen</td>
<td>Ewen Knight Corporation, Massachusetts U.S.A</td>
</tr>
<tr>
<td>Dr. B.J. Bok</td>
<td>Harvard Observatory, U.S.A</td>
</tr>
</tbody>
</table>
Harry Wendt

Contribution of the Division of Radiophysics Potts Hill & Murraybank Field Stations to International Radio Astronomy

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. C.R. Burrows</td>
<td>Cornell University U.S.A.</td>
</tr>
<tr>
<td>Dr. H. Tatel</td>
<td>Carnegie Institution, U.S.A.</td>
</tr>
<tr>
<td>Dr. J. Hagen</td>
<td>Naval Research Laboratory, Washington U.S.A.</td>
</tr>
<tr>
<td>Dr. F.J. Kerr</td>
<td>Radiophysics Laboratory Australia</td>
</tr>
<tr>
<td>Dr. J.L. Pawsey</td>
<td>Radiophysics Laboratory Australia</td>
</tr>
<tr>
<td>Dr. O. Storey</td>
<td>T.R.E. Malvern U.K.</td>
</tr>
<tr>
<td>Dr. A.C.B. Lovell</td>
<td>Jodrell Bank U.K.</td>
</tr>
<tr>
<td>Dr. M. Ryle</td>
<td>Cambridge University U.K.</td>
</tr>
</tbody>
</table>

Following the initial H-line survey, Christiansen returned to his solar observation program. By this stage Kerr had returned from Harvard and, together with Hindman, focused on the construction a new and more reliable receiver and on the new 36-ft Transit Parabola for use in a dedicated H-line survey of the southern sky. They were also joined by the new graduate student Brian Robinson, who would go on to lead the CSIRO’s radio astronomy group during the 1970s (Whiteoak and Sim, 2006: 265). The new receiver design had been devised by Pawsey and allowed for multi-channels, the first of its kind. Instead of using a narrow band that was swept over a line profile, a series of fixed frequency channels was used (see section 10.4.1).

Preliminary observations began almost immediately upon completion of the aerial and while the new multi-channel receiver was still under development. The first observations made were of the Magellanic Clouds using only a single channel of the new receiver. These were the first ever observations of H-line emission from another galaxy. Kerr and Hindman presented their preliminary findings at a meeting of the American Astronomical Society, held at Boulder (Colorado) in August 1953. They also published a summary in the Astronomical Journal (Kerr and Hindman, 1953), before presenting a more detailed account in the Australian Journal of Physics (Kerr et al., 1954). In late 1953, Robinson also unsuccessfully searched for H-line radiation from M31 (Pawsey, 1954b).

For observations of the Magellanic Clouds, a series of drift scans was taken by pointing the aerial at a fixed declination and allowing the rotation of the Earth to sweep the aerial beam in right ascension. By stepping the aerial in declination a grid of measurements covering some 250 points spaced in a lattice 1° in declination (the aerial beam width) and 10 minutes in right ascension was obtained. Figure 178 shows an example of the line profiles obtained for the Small Magellanic Cloud.
The output of the receiver was calibrated in terms of the aerial temperature. The temperatures change ($\Delta T$), correspond to the r.m.s. noise fluctuations and is related to the noise factor by the following equation:

$$\Delta T = \frac{2^{1/4}(N - 1)T_o}{(\tau B_c)^{1/2}}$$  \hspace{1cm} (14)

where

- $N$ is the noise for the continuous spectrum;
- $T_o$ is the ambient temperature;
- $\tau$ is the output time constant; and
- $B_c$ is the Bandwidth of the single channel.

For the observations of the Magellanic Clouds the receiver parameters were $N = 6$, $\tau = 15$ sec, $B_c = 40$ KHz, which gave a temperature fluctuation of 2.7 K. Correcting for the wideband output, the brightness temperature could be calculated. The highest brightness temperatures observed were about 30 K, which is about a quarter of the brightness temperature observed for our own Galaxy. Figure 179 shows the distribution of Small Magellanic Cloud brightness temperature for four different radial velocities.

Figure 178: Examples of H-line profiles obtained from the Small Magellanic Cloud (after Kerr et al., 1954: 303).
Figure 179: An example of the brightness distribution of line emission from the Small Magellanic Cloud at four different radial velocities (after Kerr et al., 1954: 302).

From the brightness temperature, the total energy received from a particular direction can be calculated in terms of the area under the line profiles. Kerr and Hindman referred to this as the integrated brightness, which is equivalent to the integrated intensity in optical spectroscopy. The integrated brightness \( B_{\text{int}} \) in units of \( \text{Wm}^{-2} \text{sterad}^{-1} \), is given by the following equation:

\[
B_{\text{int}} = \frac{2k}{\lambda^2} \int T \, dv
\]

where

- the factor 2 covers both polarisations;
- \( k \) is Boltzmann’s constant;
- \( T_v \) is the brightness temperature; and
- \( v \) is the frequency.

Figure 180 shows the contour diagram of the integrated brightness of the two Magellanic Clouds with a contour interval of \( 7 \times 10^{-16} \text{ Wm}^{-2} \text{ sterad}^{-1} \).
Similarly, the median radial velocity for each line profile can be calculated and a contour diagram of the velocities produced, as shown in Figure 181.

These preliminary observations quickly confirmed the value that radio astronomy could bring to the study of galactic structure through observation of neutral hydrogen (HI). Although the Magellanic Clouds had been extensively studied at optical wavelengths, the new radio frequency observations provided a
range of new insights. The first of these was that the area of HI emission was much larger than the optical size determinations. Also, the Small Magellanic Cloud was nearly the same size as the Large Magellanic Cloud, which was a very different result from the optical view shown in Figure 182.

The large HI content of the Small Magellanic Cloud was not expected as it had been assumed that because of the low dust content of the Cloud there would also be a low concentration of HI. The HI emission showed that there was almost an equal mass present in both Magellanic Clouds. Assuming an optically-thin distribution, an estimate of \(6 \times 10^8\) solar masses for the Large Magellanic Cloud and \(4 \times 10^8\) solar masses the Small Magellanic Cloud was determined. The Small Magellanic Cloud also showed a very prominent wing extension toward the large cloud that was also faintly present in optical studies.

Optical determinations of velocities in the Magellanic Clouds had been limited to observations of 17 emission nebulae in the Large Cloud and only one in the Small Cloud (Wilson, 1944). There was also some dispute as to whether motions in the clouds were due to rotation or translative motion of the Magellanic Clouds through space. The H-line radial velocities showed that both of the Magellanic Clouds appeared to be rotating about a common centre of gravity consistent with earlier suggestions from optical observations.

After publishing their preliminary findings Kerr collaborated with G. de Vaucouleurs, who was a Visiting Fellow at Mount Stromlo Observatory as part of the Yale-Columbia Southern Station program. De Vaucouleurs had been studying the Magellanic Clouds, and like Oort, quickly realised the potential that collaboration with a radio astronomer could bring to an understanding of large scale structures of these galaxies. His optical observations had shown that both Clouds exhibited spiral structure in their outer...
regions and that the Clouds were flattened systems inclined to the line of sight at a distance of approximately 46 kpc as shown in Figure 183 (De Vaucouleurs, 1954a,b, 1955a,b,c,d).

![Figure 183](image_url)

Figure 183: The relationship of the Large and Small Magellanic Clouds to our Galaxy and the Sun. The dotted line shows the approximate extent of HI (after De Vaucouleurs, 1955b: 229).

The H-line observations generally supported the conclusions de Vaucouleurs had reached from optical observation. However, they also indicated some important differences. By examining the rotational curves of both of the Clouds it was clear that the radio centre of rotation was somewhat displaced from that derived from optical observations. The optical observations had suggested an asymmetrical rotation as shown in Figure 184. This seemed physically unlikely and the radio observations supported a much more symmetrical rotation based on the displaced centre of radio emission. Figure 185 shows the equivalent radio rotation curve to that shown for the optical observations in Figure 184.
Figure 184: Optical rotation curve for the Large Magellanic Cloud with respect to the optical centre. The top chart is the full scatter diagram with solid dots representing points within ±20° of the central axis. The bottom chart is the best fit curve (after Kerr and De Vaucouleurs, 1955: 512).
The Small Magellanic Cloud also showed a displaced HI centre of rotation compared to the optical observations and was tilted at a somewhat smaller angle (30°) than the Large Cloud. The H-line rotational curve is shown Figure 186.

Figure 185: The H-line rotation curve for the Large Magellanic Cloud based on the radio centre (after Kerr and De Vaucouleurs, 1955: 512).

Figure 186: H-line rotational curve for the Small Magellanic Cloud based on the radio centre of rotation (after Kerr and De Vaucouleurs, 1955: 515).
In theory the radio observations could be used to estimate the tilt of the plane of the Magellanic Clouds with respect to the line of sight. The rotational velocity \( (v_r) \) can be calculated based on the relation:

\[
v_o - v_r = v_r \cos \theta \cos i
\]  

(16)

Where

- \( v_o \) is the velocity observed;
- \( v_r \) is the radial velocity of the system as a whole;
- \( \theta \) is the observed azimuth angle; and
- \( i \) is the angle of inclination to the line of sight.

Unfortunately, the face-on tilt of the Large Magellanic Cloud was at a point where the method was insensitive to variations in tilt. The radio observations suggested that the tilt may be larger than the 65° tilt indicated from optical observations. However, the data were not of sufficient accuracy to provide a definitive estimate.

The systematic radial velocity of the two Magellanic Clouds was estimated by taking all of the medium radial velocities and weighting each according to its associated brightness. This gave values of +280 and +161 km/sec for the Large and the Small Magellanic Clouds respectively prior to removal of components due to solar motion and galactic rotation. This compared well to earlier optical observations.

Given an estimate of radial velocity, it was also possible to estimate the mass of both Magellanic Clouds. Kerr and de Vaucouleurs examined this problem in a separate paper (Kerr and de Vaucouleurs, 1956). Mass estimates prior to this had been tentative at best. In examining the radial velocity, a difference between the peak and medium velocities had been noted. It appeared that the medium velocities represented regions away from the equatorial plane whereas the peak profiles appeared to be associated with the plane. For the purposes of the Magellanic mass calculations the peak curve was used. Although the Clouds appeared to have more complex structures than regular spiral galaxies, no extensions to theoretical models were available at this time and as such those applying to regular spiral galaxies were used. The mass estimates obtained from a rotation curve alone yield only a lower limit of mass. This is due to the curves being insensitive to mass in the outer parts of the galaxy and it also ignores random motions which were present in the hydrogen distribution.

The observed rotation curves were somewhat smoothed by the 1.4° aerial beam and these were corrected as shown in Figure 187.
Three different methods were used to calculate the mass. The first was to examine the Keplerian branch. This gave close agreement to a curve produced by a central point of mass of $1.5 \times 10^9$ solar masses. The second method used was the thin disk approximation (Wyse and Mayall, 1942). This yielded a mass estimate of $1.73 \times 10^9$ solar masses. The third method was based on the oblate spheroid approximation (Perek, 1950), giving a mass estimate of $1.93 \times 10^9$ solar masses. Bearing in mind that any radial velocity determination was sensitive to the tilt angle, Kerr and de Vaucouleurs adopted a mass value of $1.85 \times 10^9$ solar masses for the Large Magellanic Cloud assuming a tilt angle of $i = 65^\circ$. This provided a minimum estimate of the mass. Allowance was then made for the observed random motions in the two Clouds and extrapolation of the spherical hydrogen shell which gave a best estimate of $3.0 \times 10^9$ solar masses. Increasing the tilt angle to $70^\circ$ or $75^\circ$ would yield higher mass estimates of $4.3 \times 10^9$ and $7.1 \times 10^9$ solar masses respectively. Using the Large Magellanic Cloud as an analogy, an estimate for the Small Cloud was made of $1.3 \times 10^9$ solar masses. This was the first time that the masses of the Magellanic Clouds had been estimated on any basis other than a small sample of optical observations.

The differential radial velocity of the two Magellanic Clouds based on the H-line measurements was approximately 50-60 km/sec. Kerr and de Vaucouleurs showed that by assuming the Clouds were moving as an isolated system, their combined mass ($M$) could be related to the relative orbital velocity ($v$) by the following expression:

$$M = \frac{v^2}{G \left( \frac{2}{r} - \frac{1}{a} \right)}$$

(17)
where

\[ G \] is the gravitational constant;
\[ r \] is the distance between the two clouds; and
\[ a \] is the semi-major axis of the relative orbit.

The observed differential radial velocity implied that the Magellanic Clouds could only be in a closed orbit if their combined masses exceeded \( 5 \times 10^9 \) solar masses. For a circular orbit the combined mass would need to be greater than \( 10 \times 10^9 \) solar masses. Therefore, they concluded that the two Clouds were in a hyperbolic or near parabolic orbit relative to one another. They also noted that the two Clouds cannot be considered independent of our own Galaxy and must be treated as a three-body system.

Determination of the mass of the systems was critically dependent on the orientation of the axis of rotation. Measurement of the tilt of the Clouds has remained problematic. In 1972 de Vaucouleurs revised the tilt estimate for the Large Magellanic Cloud to \( i = 27^\circ \pm 2^\circ \) based on both optical and HI evidence (De Vaucouleurs and Freeman, 1972). Over time it was further revised to a generally accepted value of \( i = 45^\circ \) (e.g. Sparke and Gallagher, 2000: 137). More recent evidence suggesting a warp in the disk of the Large Cloud has suggested a tilt of \( i = 35^\circ \) (Olsen and Salyk, 2002).

While Potts Hill’s location in the Southern Hemisphere provided an ideal opportunity to examine the Magellanic Clouds, the primary purpose of the H-line survey was to examine the southern Milky Way. This survey work commenced in earnest in 1954 with completion of the four-channel H-line receiver. Joining Kerr and Hindman was Martha Stahr Carpenter who was visiting Radiophysics from Cornell University. Although Christiansen and Hindman had published the first substantial survey of H-line radiation (Christiansen and Hindman, 1952a,b), the Dutch group working at Leiden quickly made significant progress mapping the northern Milky Way and set the standard for galactic examinations based on H-line observations (Kwee et al., 1954; Oort, 1953; van de Hulst et al., 1954). The leader of this group, Oort, had earlier established much of the theoretical underpinning for the study of galactic structure (Oort, 1952). During the 1900s a phenomenon for stars close to the Sun had been noted whereby their proper motions (\( \mu \)) varied with galactic longitude (\( l \)) as the function:

\[ \mu \propto \cos 2l \]  \hspace{1cm} (18)

Oort (1927) was the first to propose that this phenomenon could be explained by galactic rotation. Building on their survey work of the northern sky the Dutch group soon developed a picture of the spiral structure of the Galaxy (Schmidt, 1957; Westerhout, 1957).
Although the Australian H-line survey began in 1954, it was not until 1959 that the full observational results of the survey were published in detail (Kerr et al., 1959). However, during this period there were many presentations and discussions on findings of the southern H-line survey at conferences (e.g. Carpenter, 1957). In addition there were several publications of initial findings (Kerr, 1957, 1958b; Kerr et al., 1956) and a summary paper which appeared in *Nature* (Kerr et al., 1957).

The Australian H-line survey itself consisted of examination of an 8° wide strip along the Galactic Equator with the aim of determining the three-dimensional distribution of neutral hydrogen within the strip. Observations were taken along 41 selected paths across the Galactic Equator at a variety of longitudes ranging from $l = 175^\circ$ to $l = 5^\circ$ (under the pre-1959 galactic co-ordinate system). Drift scans were used in most cases by holding the aerial stationary while the Earth rotated. Scans were taken using the 4-channel receiver which covered 4 adjacent 40 KHz bands. As this was not sufficient coverage to encompass the full Doppler shift of the line profiles, scans needed to be repeated with the receiver channels shifted to a new set of frequency bands. This was done by overlapping coverage to ensure consistency of results. It also gives some insight as to how labour intensive the survey was being limited to only four channels. Ultimately a new 48-channel receiver was built and tested at a new field station at Murraybank, giving a significant improvement in the time taken to obtain line profiles (Orchiston and Slee, 2005a: 161). Figure 188 shows a diagram of the 41 scan paths taken across the Galactic equator.

![Figure 188: H-line survey paths through the Galactic Equator. Both pre- and post-1959 Galactic Equators are shown. Celestial coordinates (top scale) are epoch 1955. Galactic co-ordinates (bottom scale) are pre-1959 coordinates (after Kerr et al., 1959: 277).](image-url)
The first published material to appear on the preliminary results of the Potts Hill southern galactic H-line survey was a short summary paper that appeared in the *Astronomical Journal* (Kerr et al., 1956). This paper reported on a tentative picture of the spiral structure of the southern portion of the Galactic Plane. The initial examination of the H-line profiles at longitudes between $l = 260^\circ$ and $l = 275^\circ$ showed that the outer spiral arms appeared to be trailing and showed an increasing southward shift in galactic latitude with distance in this region. These results were consistent with the Leiden observations and also showed that the hypothesis proposed by Edmondson (1955) - that the mean galactic motions would depart from a circular motion - was unlikely. These findings had first been reported by Carpenter in a paper summarising the work of the Potts Hill survey during an IAU meeting held at Jodrell Bank in August 1955. The paper was only published in 1957 (as part of the conference proceedings)(Carpenter, 1957). It contained slightly more information on the provisional picture of the southern galactic spiral arm structure, as shown in Figure 189, as well as the provisional contour profiles for $l = 260^\circ$, $270^\circ$ and $275^\circ$, as shown in Figure 190.

![Figure 189: The provisional diagram of the galactic spiral structure based on the Potts Hill observations (after Carpenter, 1957: 15)](image-url)
Figure 190: H-line radial velocity contour profiles for the three galactic longitude sections $l = 260^\circ$ (top), $270^\circ$ (middle) and $275^\circ$ (bottom) showing three spiral arms in this direction (after Carpenter, 1957: 15).

Figure 190 shows three distinct spiral arms. One of the arms lies within the radius of the Sun’s orbit around the Galactic Centre and the other two arms lie outside of this radius. Carpenter noted that the ridge that extends from the zero radial velocity point at $l = 270^\circ$ coincided with the position of the Coal Sack.

In May 1957 Kerr published a short note in the *Astrophysical Journal* noting that the southward shift of the spiral arms, which had been discussed in earlier results, appeared to indicate a warp in the galactic disk that coincided with the direction of the Magellanic Clouds (Kerr, 1957). On face value the observation suggested a tidal influence from the Magellanic Clouds. However, the size of the warp was too large to be
caused purely by a simple gravitational effect and Kerr suggested a more complex interaction effect was likely. This same effect was also independently noted by Burke (1957).

Finally, in October 1957, a full summary of the southern galactic survey was published in *Nature* (Kerr et al., 1957). Although the results of the northern sky survey had been known since 1954, this was the first time that the full southern and northern sky survey results appeared together. Even then, the analysis of the observations had not been fully reduced. No allowance in these results had been made for the smoothing effect of the aerial beam or for random motions within the interstellar neutral hydrogen clouds. However, it was anticipated that these effects would not materially alter the preliminary results.

Drawing on the Leiden observations of the northern sky, for the first time a full-sky map of the structure of the galactic spiral arms could be made. Figure 191 shows the first composite map that combined the Potts Hill and Dutch results.

![Composite diagram of the spiral structure of the Galaxy based on observations from Potts Hill (left half) and Leiden (right half). The Galactic Centre is marked by a cross and the Sun’s position and assumed circular orbit is also shown. A distance of 8.2 kpc from the Sun to the Galactic Centre is assumed (after Kerr et al., 1957: 677).](image-url)
Figure 191 shows a series of dots that mark the peak line profiles of individual measurements from the Potts Hill data only. Shading joining these dots shows the proposed spiral arm structures. The small open dots shown in the inner left of the diagram correspond to a broad peak on a given profile which was presumed to indicate a spiral arm seen nearly end-on. The distances indicated on the diagram were derived from the radial velocity measurements of the peaks using the same techniques that had been developed in Leiden. The inner 2 kpc of the diagram for the Potts Hill observations had been left deliberately blank due to difficulty in determining the component related to a spiral arm and that due to random motions.

The southern side of the chart showed four distinct spiral arms, which were identified (moving outwards from the Galactic Centre) as the Scutum-Norma arm, the Sagittarius arm, the Orion arm and the Perseus arm. The Sun was believed to be located in the inner edge of the Orion arm. The outer boundary of the Galactic disk appeared to occur at approximately 15 kpc from the Galactic Centre. This identification of the spiral arms has fared well in modern times, the only difference being that the Scutum-Norma arm is now believed to be two separate arms (the Norma arm and the Scutum-Crux arm). The Orion arm is generally referred to as the Local arm. Although today the use of neutral hydrogen to map spiral arms is generally discounted in favour of other techniques, the general picture obtained in Figure 191 was a remarkable achievement. It was not until 1976 (Georgelin and Georgelin, 1976) that a more accurate representation of the spiral arms was produced (Figure 192).

Figure 192: A revised spiral arm map based on optical and radio data with the major arms annotated. Note that the Orion arm was not considered a major feature in this map (after Georgelin and Georgelin, 1976: 74).
It should be noted that the different appearance of the two sides of Figure 191 was due to the different techniques used. The shading in the Leiden results was an ‘artist’s impression’ based on following the density contours. The Potts Hill result is a schematic representation based only on the well-defined features of the line-profiles. While these different techniques produced a different appearance there was still good general agreement between results. Overall the results clearly showed that the Galaxy has a multi-arm structure and that the arms have a general trailing tendency based on the clockwise direction of rotation used in the diagram.

Figure 193 shows a relief map of the Galaxy with contours that show the departure, both upward and downward, from the Galactic Plane. It also indicates the position of the Large and Small Magellanic Clouds.

![Figure 193: Relief map of the Galaxy with contours indicating the departure in parsecs from the Galactic Plane. The lower portion (b) shows a cross section in the direction of the Large Magellanic Cloud (after Kerr et al., 1957: 678).](image)

Figure 193 clearly illustrates the observed southward and northward warp of the galactic disk. The neutral hydrogen in the galactic disk was observed to be confined to a thin layer approximately 250 parsecs between half density points. In the inner part of the Galaxy this disk was found to be remarkably flat and was used to determine the ‘principle plane’ of the Galaxy. The largest deviation from the principle plane is clearly seen corresponding to the direction of the Large Magellanic Cloud.
These same results were also reported by de Vaucouleurs on Kerr’s behalf at the IAU symposium on cosmical gas dynamics held at the Smithsonian Astrophysical Observatory, Cambridge, Massachusetts on June 24-29, 1957 (Kerr, 1958b).

Shortly after the Nature summary paper appeared, Kerr and Hindman published a short paper on the mass distribution of neutral hydrogen in the Galaxy (Kerr and Hindman, 1957). Particularly, they noted that neutral hydrogen does not share the same distribution as other mass in the Galaxy. Whereas the visible mass is generally concentrated toward the Galactic Centre, neutral hydrogen is relatively constant beyond 4-5 kpc and falls off rapidly toward the Centre. At the distance of the Sun the relative space density was measured at approximately 15%, while integrating measurements over the whole Galaxy showed the ratio of neutral Hydrogen to total mass was only 2%. Figure 194 shows the ratio of hydrogen to total mass.

![Figure 194](image_url)

Figure 194: The measured ratio of neutral hydrogen to total mass in the Galaxy with the space density in the equatorial plane compared to the projected density that corresponds to the distribution that would be seen from outside of the Galaxy (after Kerr and Hindman, 1957: 559).

The distinction in the mass densities was important because if the density in the region of the Sun was assumed as a generalisation of overall density in spiral galaxies, large errors would result. Measurements of M31 had shown a ratio of approximately 1%, which compared well with these results. The earlier measurements of the Magellanic Clouds had suggested ratio of 20%, which Kerr and Hindman took to indicate that the two Magellanic Clouds were much younger than our Galaxy.

The final detailed paper on the southern survey was published in the *Australian Journal of Physics* (Kerr et al., 1959). This paper contained a full set of line profiles together with a set of intensity contours plotted as a function of galactic latitude and radial velocity. An example for the contour diagrams is shown in Figure 195.
Figure 195: An example of the H-line intensity contour diagram. The galactic latitude $b$ is the 1932 Galactic coordinate system.

During 1957, Kerr spent several months visiting the Dutch group at Leiden with the specific purpose of combining data on observations from the Southern Hemisphere. This work resulted in a joint paper between the Australian and Dutch groups summarising the understanding of the Galaxy as a spiral system.
(Oort et al., 1958). This included an update of the rotation curve derived from both the Leiden and Potts Hill observations and is shown in Figure 196. It is interesting to note that the two sets of data would actually produce two slightly different rotation curves if treated individually. This is something that Kerr would examine in a later review (Kerr, 1962).

For the first time Oort et al. (1958) also published a combined density map of neutral hydrogen, as shown in Figure 197.
In the inner 3 kpc of this map a tentative identification of a new ‘expanding’ arm was shown marked by a row of arrows. Within this inner region the team found evidence of an expanding motion of the neutral hydrogen with deviations from the expected circular rotation of up to 200 km/sec. They named this arm the “3-kpc expanding arm”, a name which is still used today (although generally the “expanding” term has dropped).

The joint team also published an updated map, shown in Figure 198, of the deviation of neutral hydrogen from the principle plane of the Galaxy, as measured by the H-line observations. This plane was approximately inclined 1.5° to the then ‘standard’ plane.
The deviation map showed new detail in the region inside of the Sun’s orbit around the Galactic Centre.

Figure 197 appears to show some differences between the northern and southern parts of the Galaxy. However, this effect is largely due to the differences in reduction techniques used by the two groups. While the Australians had applied generally the same technique as the Dutch, including the same velocity model, they employed a less dramatic reduction for random motions, using a normal Eddington coefficient rather than the double coefficient used by the Dutch. Kerr also made no allowance for continuum radiation in the inner regions. These two differences resulted in less detail than the Dutch side of the map. Others (van Woerden and Strom, 2006: 12) have noted there appeared to have been some minor disagreements between the groups as to the validity of the corrections and this may have been why Kerr had not performed exactly the same reductions. This is confirmed by Kerr who noted:

“...our views about the best [reduction] procedure differed to some extent.” (Kerr, 1962: 329)
The differences in reduction techniques used by the groups was discussed in detail in a later review by Kerr (1962), who found that the velocity model used by the Leiden group would lead to an implausible spiral structure on the southern side of the Galaxy assuming that the structure and motions are symmetrical on the large scale. Kerr proposed that the results could be reconciled if it was assumed that the Sun had an outward velocity component of 7 km/s. Figure 199 shows a revised density distribution map based on the new rotational model and allowing for the outward motion of the Sun. This map shows the spiral arm structures more clearly than the original map shown in Figure 197.

![Figure 199: Revised density distribution of neutral hydrogen in the Galactic Plane based on a new rotation model and assuming an outward motion of the Sun of 7 km/s (after Kerr, 1962: 340).](image)

The combined maps provided a solid foundation for examination of our Galaxy’s HI structure. However, in later years other techniques would provide the basis for a more accurate determination of the spiral arm structure. The use of neutral hydrogen observations to determine Galactic structure has a number of shortcomings. Like all kinematic methods it is necessary to assume a rotation model to convert the observed radial velocities into distances. These models generally assume circular orbital motions and therefore do not cater for non-circular motions. For orbits inside of the Sun, the models give two possible distances for any observed radial velocity and this can present difficulties in determining which distance is applicable for a given observation. Possibly the largest issue with the neutral hydrogen observations was
that the observations were the result of integration along the line of sight. This means that it is not clear whether a given line profile’s characteristics are the result of streaming motions, a density concentration, or a variation in gas temperature (Burton, 1973). In later years, and with the discovery of the hydrogen recombination and the carbon monoxide spectral lines, the focus shifted to measuring these more discretely-concentrated sources to determine our Galaxy’s structure.

Given the growing body of evidence from the radio surveys at the 1955 General Assembly held at Dublin the International Astronomy Union appointed Sub-Commission 33b “...to investigate the desirability of a revision of the position of the galactic pole and of the zero point of galactic longitude”. The members of the Sub-Commission were A. Blaauw, C.S. Gum (who was unfortunately killed in a skiing accident in Switzerland on 28 April 1960 shortly after the completion of the Sub-Commission’s final report), J.L. Pawsey and G. Westerhout.

Up until this time, the Galactic Pole had been located at right ascension 12$^h$ 40$^m$, declination +28º (1900.0) and was used as the basis for the standard conversion to galactic coordinates in the *Lund Observatory Conversion Tables* (Ohlsson, 1932). By the time of the next General Assembly meeting in Moscow in 1958, enough preliminary evidence had been gathered, particularly from the neutral hydrogen surveys, to recommend that it would be opportune to adopt a new system of galactic coordinates and as such the General Assembly passed a resolution for the Sub-Commission to define and announce a new system of coordinates. In March 1959 the Sub-Commission completed its investigations and communicated its decision to the General Secretary of the I.A.U. and various astronomical journals. A series of five papers was published which together formed the final recommendations of the Sub-Commission (Blaauw, 1960; Blaauw et al., 1960; Gum et al., 1960; Gum and Pawsey, 1960; Oort and Rougoor, 1960). The new position of the Galactic Pole was determined as:

\[
\alpha = 12h\ 49m\ 02s \pm 30s \ (1950.0)
\]
\[
\delta = 27º\ 22′.7 \pm 7′
\]

Figure 200 shows the position of the new Pole determined from radio observations relative to Ohlsson’s 1932 pole.
The key paper out of the five that made up the Sub-Committee’s final report was the analysis of the combined Leiden and Potts Hill neutral hydrogen observations (Gum et al., 1960). In this analysis, Gum, Kerr and Westerhout essentially conducted a new analysis of data from the two surveys. By selecting a number of points within the inner 7 kpc of the Galaxy, a least mean square analysis of different selection groups showed close agreement and indicated that this region was virtually indistinguishable from the principle plane of the Galaxy. Figure 201 shows the distribution of points of maximum hydrogen density plotted by heights ($z$) above the new Galactic Plane against distance ($R$) from the Galactic Centre. The warping of the neutral hydrogen disk above and below the Galactic Plane is clearly evident outside of the Sun’s orbit at 8.2 kpc.
The other Potts Hill contribution was in Paper III (Gum and Pawsey, 1960), which examined the overall radio continuum and the position of the radio source Sagittarius A. A key set of observations were derived from the 600 MHz survey that was conducted at Potts Hill by Piddington and Trent (1956a,b). Figure 202 shows the positions of the radio continuum ‘ridge-lines’. The central diagram contains the 600 MHz survey data and is indicated by the filled black dots. It can clearly be seen that the narrow-beam survey data provided strong support for the newly defined Galactic Equator as determined from the neutral hydrogen measurements.

![Diagram of radio continuum 'ridge-lines'.](image)

Figure 202: Wide beam (left), narrow beam (centre) and neutral hydrogen (right) radio continuum ‘ridge-lines’. Data plotted using the 1932 galactic coordinates. The dotted sine curve indicates the newly-derived Galactic Equator (after Gum and Pawsey, 1960: 153).

By mid 1959 much of the research effort at Potts Hill had been completed, as noted in an internal report (Pawsey, 1959a). The 21-cm survey of the Milky Way had been completed although the research results
were still being written up. It was decided that the 36-ft Parabola and its equipment hut would be maintained at Potts Hill for receiver testing until such time as the new laboratory facilities, which were being constructed at Epping as part of the new headquarters for the Radiophysics Division, were completed. It was also noted that the continuing solar recording at Potts Hill, which was now the responsibility of Fairweather, would continue only as long as required to support observations using the Chris Cross at Fleurs and Wild’s solar burst investigations at Dapto. A new 48-channel H-line receiver and fully steerable 21-ft parabola were constructed at a new field station at Murraybank in 1956 and were used to continue the H-line program of observations and to act as a test bed for equipment that would later be deployed for the Parkes Radio Telescope (Orchiston and Slee, 2005a: 160).

10.5.3. Jupiter Burst Observations

During February and March 1956, Potts Hill was used as a secondary field station as part of the investigation of radio emissions from Jupiter by Gardner and Shain (1958). The main instruments were located at the Fleurs field station some 25 km to the west of Potts Hill.

Radio emission from Jupiter had first been detected in the U.S.A. by Burke and Franklin (1955) using a ‘Mills Cross’ operating at 22.3 MHz. It was only after this discovery that Shain found, by examining 18.3 MHz Hornsby Valley field station records, that he had in fact detected the Jovian burst emissions in 1951 but that they had gone unnoticed at the time. In examining the 1951 records Shain (1955, 1956) found that the emission appeared to come from a localised region on the planet (Orchiston and Slee, 2005b).

In order to compare results with those from Fleurs, at Potts Hill a simple dipole antenna was suspended between two wooden poles and connected to a receiver operating at 19.6 MHz. This formed part of a spaced-aerial experiment to determine if the scintillations in the radio emission were inherent in the source itself or caused by the ionosphere. The receivers at both sites were closely tuned to avoid discrepancies caused by sharp spectral variations in the burst signals. The high levels of radio interference at Potts Hill meant that only three pairs of results from the Potts Hill and Fleurs were available for comparison. Figure 203 shows an example of the spaced-receiver records taken simultaneously at Potts Hill and Fleurs.
An examination of the records showed significant differences between the two sites with some bursts observed at only one of the two sites. There also appeared to be timing differences between the sites and some differences in the burst characteristics. Gardner and Shain (1958) concluded that these differences between the sites indicated that the terrestrial ionosphere must have a considerable effect on the time variations of the Jupiter radiation.

Jovian observations over a 200 km baseline by Slee and Higgins (1968) later showed that the so-called bursts are due to scintillations caused by diffraction in the solar wind.

10.5.4. 1952 URSI General Assembly

In recognition of the growing contribution of Australian research to the new science of radio astronomy, the 10th General Assembly of the URSI was held in Sydney from 11 to 23 August 1952 (see Robinson, 2002). This Section provides a brief discussion of the conference and the role played by the Potts Hill researchers.

The organising committee for the Sydney event consisted of Sir J. Madsen (Chairman), Dr. E.G. Bowen, Dr. R.N. Bracewell (Secretary), Mr. J.N. Briton, Mr. F.J. Lehany (Treasurer), Dr. D.F.M. Martyn, Dr. G.H. Munro, Dr. J.L. Pawsey. All but Madsen, Martyn and Munro were Radiophysics staff.

In March 1952 Pawsey sent out a memo to all Research Officers within the Radiophysics Division calling for the submission of papers for the General Assembly (Pawsey, 1952e). Additionally, he also sent a copy of the memo to K.C. Westfold and wrote a separate letter to Mrs. Hall (Ruby Payne-Scott) asking if she and Alec Little would like to submit a paper. Pawsey stated in this letter:
“...in my ‘provisional’ list, unofficial, I include your work with Alec as one of our star efforts.” (Pawsey, 1952d).

Pawsey also noted:

“...if such a paper is to be presented verbally at the Conference I think you would do it excellently.” (ibid.).

Payne-Scott wrote back on 20 March noting that Alec Little was on leave and therefore she had been unable to discuss the submission with him (Payne-Scott, 1952). She included a hand-written one-page outline titled, “The Relation between Solar Radiation at Metre Wave-Lengths and Other Solar Phenomena”. The outline included two key sections that concluded that Noise Storms originate high in the corona with different frequencies appearing at different levels, probably excited by magnetic fields associated with sunspots, while Outbursts were probably caused by excitation from the same particles that were presumed to cause magnetic storms on Earth. On 26 March, Pawsey replied that he had discussed the outline with Paul [Wild] and that he also favoured the idea of presenting the paper (Pawsey, 1952a). He concluded that all three should meet to discuss the submission when Wild returned from a visit to the Dapto field station. For unknown reasons no further correspondence on this subject appears on file, and although Payne-Scott did attend the Conference, she did not submit a paper.

At the end of April 1952, the Radiophysics Division formally submitted four papers for consideration:

4) A Multiple Interferometer for Solar Observation at a Wavelength of 21 cm. By W.N. Christiansen (Paper 279).

All four papers were accepted, two being based on the work at Potts Hill. In late June, Piddington wrote to Pawsey asking to include a late paper he was preparing with Davies titled, “Thermal Radiation from the Sun and the Source of Coronal Heating” (Piddington, 1952). Pawsey replied on 10 July that he considered that only in exceptional circumstances would a late request be granted and that he did not consider the paper to be of sufficient importance for its late inclusion (Pawsey, 1952b). He did however suggest that another of Piddington’s papers on sources of galactic radiation, did warrant inclusion and he was prepared to support its late submission. This paper was accepted, and, along with another paper by J.W. Dungey from The School of Physics at the University of Sydney, made up the final two papers from Australia submitted to Commission V:


Unfortunately the Executive Committee of the URSI decided to discontinue publication of Part II (Papers) of the Assembly Proceedings and therefore the presented papers were not published.

In the report to the URSI on the Australian National Committee of Radio Science 1950-52 under Commission V – Radio Astronomy the following was noted:

“The greater part of the research in radio-astronomy in Australia is carried out by the Radiophysics Laboratory of the C.S.I.R.O. in Sydney, the observations being taken at a number of field stations near the fringe of the built up area. The largest of these is at Potts Hill. This laboratory is concerned with cosmic and solar radio waves.”

The conference itself was a major success with many strong bonds formed between the visiting researchers and the staff from the Division of Radiophysics. It was at this conference that Christiansen established the relationship with the French group that would lead to him spending a year in France. Also, it provided the opportunity for nearly all of the people involved in the initial H-line detection to meet face-to-face. Figure 204 shows the Radiophysics members who attended the conference together with their counterparts from France, England, the Netherlands and the U.S.A.
As an adjunct to the conference, visits were also organised to three of the Radiophysics field stations, one of these being Potts Hill. Figure 205 shows Professor Balthasar van der Pol from the Netherlands and Sir Edward Appleton inspecting the E-W Solar Grating Array with Christiansen standing next to one of his antennas. This photograph was reproduced in several Australian newspapers at the time.
The conference was recounted by Frank Kerr (1953c) in an article in the January 1953 edition of Sky & Telescope which helped to further publicise the contribution of Radiophysics (and hence Potts Hill) research amongst the wider astronomical community.

For further recollections of the 1952 URSI meeting see Robinson (2002) who attended the meeting having graduated in Physics in 1951.